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A situation risk awareness approach for process systems safety

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A B S T R A C T

Promoting situation awareness is an important design objective for a wide variety of domains, especially for process systems where the information flow is quite high and poor decisions may lead to serious consequences. In today's process systems, operators are often moved to a control room far away from the physical environment, and increasing amounts of information are passed to them via automated systems, they therefore need a greater level of support to control and maintain the facilities in safe conditions. This paper proposes a situation risk awareness approach for process systems safety where the effect of ever-increasing situational complexity on human decision-makers is a concern. To develop the approach, two important aspects – addressing hazards that arise from hardware failure and reducing human error through decision-making – have been considered. The proposed situation risk awareness approach includes two major elements: an evidence preparation component and a situation assessment component. The evidence preparation component provides the soft evidence, using a fuzzy partitioning method, that is used in the subsequent situation assessment component. The situation assessment component includes a situational network based on dynamic Bayesian networks to model the abnormal situations, and a fuzzy risk estimation method to generate the assessment result. A case from US Chemical Safety Board investigation reports has been used to illustrate the application of the proposed approach.

1. Introduction

Since the beginning of the industrial revolution, many serious accidents at large-scale technological systems that have had grave consequences, such as those at Three Mile Island, Bhopal and Chernobyl, have primarily been attributed to human error. In the vast majority of these accidents, the human operator was struggling against significant challenges such as data overload and the task of working with a complex system. In fact, operators are not the cause of these accidents, but they have inherited the problems and difficulties of technologies created by engineers. Operators generally have no difficulty in physically performing their tasks, and no difficulty in knowing the correct action to do, but they are stressed by the task of understanding what is going on in the situation (Endsley, 2006). Over the last two decades, a great deal of research has been undertaken in the area of Situation Awareness (SA).

Situation awareness, a state of mind in humans, is essential for conducting decision-making activities. It concerns the perception of elements in the environment, the comprehension of their meaning, and the projection of their status in the near future (Endsley, 1995b). The primary research in this field was undertaken in the aviation industry, where pilots and air traffic controllers are under considerable pressure to develop better SA. One review of over 200 aircraft accidents found that poor SA was the main causal factor (Endsley, 1997). A review in other domains, such as nuclear power plant, showed that this is not a problem limited to aviation, but one faced by many complex systems (Endsley, 2006). Successful system designs must deal with the challenge of combining and presenting the vast amounts of data now available from many technological systems to provide true SA, whether it is for a pilot, a physician, a business manager, or an automobile driver.

In the process industry, the last two decades have been marked by a significant increase in automation, advanced control, on-line optimization and technologies that have significantly increased the complexity and sensitivity of the role of operators and their teams. Nowadays, process operators have to rely on human computer interaction (HCI) principles to observe and comprehend the overwhelming amount of rapidly changing process data. They are often moved to a control room far away from the physical process, where automated systems pass more and more information to them, so they have to handle more data and more responsibility. In the presence of all this data, operators are finding that they have even less awareness than before about the situations they are controlling. This has led to a huge gap between the massive amount of data produced and disseminated and the operator's ability to effec-

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tively assimilate the required data and to make timely, accurate decisions (Endsley and Garland, 2000). This emphasizes the importance of SA in process systems, but paradoxically the literature review shows that the majority of process safety studies have focused on the technical issues and have often neglected SA. This may be due to the increased complexity introduced when dealing with the human factors of a system, while hardware reliability techniques are relatively mature and well understood (Sandom, 2001).

Situation awareness is quite likely to be at the root of many accidents in process control, where multiple goals are pursued simultaneously, multiple tasks need the operator's attention, operator performance is under high time stress, and negative consequences associated with poor performance are expected. Kaber and Endsley (1998) believe that many of the performance and safety problems that currently occur in the process control arena are the result of difficulties with the operator's SA, such as:

- Failure to detect critical cues regarding the state of a process control system.
- Failure to properly interpret the meaning of information perceived through process control interfaces.
- A lack of understanding of individual task responsibilities and the responsibilities of other control operators.
- A lack of communication between operators functioning in teams.

Sneddon et al. (2013) analyzed offshore drilling accidents and their results show that more than 40% of such accidents are related to SA, and that the majority of those SA errors (67%) occurred at the perceptual level, 20% concerned comprehension, and 13% arose during projection. In the case of the Texas City, TX BP Amoco Refinery explosion on 23 March 2005, 15 workers were killed and 170 injured when a column was overfilled, overheated, and over-pressurized on startup. The key problem identified in this catastrophic event was the difficulty experienced by the operator in maintaining an accurate awareness of the situation while monitoring a complex, fast moving environment (Pridmore, 2007). As can be seen, loss of SA, poor SA and lack of SA as identified causal factors are now popular terms in accident investigation reports (Salmon and Stanton, 2013). However, some researchers such as Dekker (2013), question whether the loss of SA, a psychological construct, can result in human operators being liable for mishaps and argue that SA itself is not the cause of accidents.

In a process system, operators' tasks include information gathering, planning, and decision making. In addition, according to ALARP, operators should demonstrate that the risks associated with the functioning of a facility are sufficiently low (Melchers, 2001), and that they monitor the system continually to ensure that it is stable and functioning normally. During abnormal situations, a well-trained operator should comprehend a malfunction in real time by analyzing alarms, assessing values, or recognizing unusual trends on multiple instruments. Usually, many alarms from different systems are triggered at the same time during an abnormal situation, making it difficult for the operator to make a decision within a very short period of time. If several abnormal situations occur at the same time, decisions need to be made particularly quickly. Operators are frequently unable to judge which situation should be given priority in a short timeframe, when confronted with complex abnormal situations, yet operators must respond and make decisions quickly to recover their units to normal conditions. Under these circumstances, the mental workload of operators rises sharply and too high mental workload possibly increases their error rate (Hsieh et al., 2012; Jou et al., 2011). Therefore, a system is needed to support operators' SA in understanding and assessing the situation and to assist them to take appropriate actions.

This paper introduces a new situation risk awareness approach for process systems safety where the degree of automation and complexity is increasing and the number of operators is decreasing, and each operator must be able to comprehend and respond to an ever increasing amount of risky status and alert information in abnormal situations. Efforts have been made to develop new SA approaches for military purposes and maritime security (Baader et al., 2009; Farahbod et al., 2011), and other studies have used machine learning, expert systems and ontology (Brannon et al., 2009; Naderpour and Lu, 2012a, b; Nguyen et al., 2009). However, none of these is appropriate for supporting operators' SA in abnormal situations. The situation risk awareness approach includes an evidence preparation component in which, based on the online conditions and process monitoring system, the current state of the observable variables is prepared as soft evidence to use in the next component. The approach also contains a situation assessment component that uses risk indicators to determine abnormal situations, minimize the number of alarms, and determine the investigation priority of abnormal situations. In addition, simple and dynamic Bayesian networks are used to develop the model base of the approach.

The paper is organized as follows. Section 2 presents the background and related works. Section 3 describes the situation risk awareness approach. Section 4 introduces the SA measurement and dealing with uncertainty. A case from the US Chemical Safety Board investigation reports (www.csb.gov) is presented in Section 5 to illustrate the feasibility and benefits of the proposed approach. Finally, the conclusion and future work are provided in Section 6.

2. Background and related works

This section describes the background to SA, dynamic Bayesian networks and fuzzy sets, and outlines related works.

2.1. Situation awareness

A situation is a collection of objects which have relationships with one another and the environment, and an object is a physical entity: something that is within the grasp of the senses. Additionally, SA can be described as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1995b). This SA model follows a chain of information processing from perception, through interpretation, to projection. From the lowest to the highest, the levels of SA are as follows (Endsley, 2006; Stanton et al., 2001):

- *Perception:* Perception involves the sensory detection of significant environmental cues. For example, operators need to be able to see relevant displays or hear an alarm.
- *Comprehension:* Comprehension is the understanding of the meaning or significance of that information in relation to goals. This process includes developing a comprehensive picture of the world.
- *Projection:* Projection consists of extrapolating information forward in time to determine how it will affect future states of the operating environment. Higher levels of SA allow operators to function in a timely and effective manner, even with very complex and challenging tasks.

Fig. 1 paves the way to a better understanding of the definition of both 'situation' and 'SA'. It shows four planes, each of which refers to a different level of abstraction. The bottom layer shows the